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Probabilistic Failure Assessment with Application to Solid Rocket Motors

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Introduction

A quantitative methodology is being developed at JPL for assessment of risk of failure of solid rocket motors. This probabilistic methodology employs best available engineering models and available information in a stochastic framework. The framework accounts for incomplete knowledge of governing parameters, intrinsic variability, and failure model specification error. Earlier case studies have been conducted on several failure modes of the Space Shuttle Main Engine (refs. 1,2,3). This paper describes work in progress on application of this probabilistic approach to large solid rocket boosters such as the Advanced Solid Rocket Motor for the Space Shuttle. Failure due to debonding has been selected as the first case study for large solid rocket motors (SRMs) since it accounts for a significant number of historical SRM failures. Impact of incomplete knowledge of governing parameters and failure model specification errors is expected to be important.

Debond Failure in SRMs.

SRM failure modes generally fall into the categories of debonding, nozzle failure, propellant cracking, combustion instability, field joint failure, O-ring failure, and case burst. As an initial case study, this work is focussing on failure due to debonding. Motivation for looking at debond failure is clear, as stated in reference 4:

It is probably a conservative estimate that well over half of all mishaps (and this includes the latest space shuttle disaster) are due to the flame front prematurely reaching the chamber walls, or getting into places where it should not. Usually the cause is a failure of the propellant-liner bond, or the propellant-to-insulation bond, and sometimes insulation to chamber wall bond.

The problem of solid propellant debonding has received considerable attention in the literature. For example, in reference 5, a finite element computer code was developed for evaluation of the state of stress in solid propellant case liner bond regions. Also, a closed form fracture mechanics solution which accounts for the dissimilar material properties on either side of the bondline was proposed for predicting debond growth. Reference 6 discussed both stress-strain and fracture mechanics techniques for predicting bondline failures.

The underlying chemistry and environment of the bond region are quite complex. These issues are addressed in references 7 and 8. However it may not be necessary to incorporate all of the complexity considered in these references in order to satisfactorily assess reliability. Inherent variability of various parameters in the bonded region may be accounted for through the statistical approach described briefly below, and in detail in reference 1.

The Debond Failure Mode. The sequence of events leading to failure by debonding is shown in Figure 1. Failure due to debonding begins as a defect, or crack, in the bond region, referred to as the "Initial State" in Figure 1. This defect may occur as a result of normal manufacturing processes, or perhaps as a result of foreign particle inclusion. In general there will be a distribution of size and locations of a number of defects. These defects may grow prior to launch as a result of induced bondline stresses from shipping

and handling loads, thermal cycling, and moisture absorption. Additional defect growth may result from vibrations during launch, axial acceleration, case pressurization, aerodynamic heating, or vibrational loads. The result can be a defect of a certain size and location such that the flame front can enter the defect region. The debonded region contributes additional surface area for burning. This can lead to uneven burn and increased pressure. If the pressure becomes higher than the design pressure, it can cause mechanical deformation and further defect growth. Case burn-through becomes a possibility, and detonation can result if the pressure rise is rapid enough (ref. 9).

The Probabilistic Failure Assessment (PFA) Methodology.

The PFA Methodology developed at JPL is a quantitative technique for estimating reliability warranted by the available information. (See reference 1 for a detailed description of PFA.) For cases of unacceptable risk, PFA identifies areas where design improvement and/or additional data are required.

The core of the PFA approach consists of analytical engineering models which characterize failure phenomena in terms of governing parameters. Such failure models typically express a failure parameter such as burst pressure, flaw size, or flaw growth rate, as a function of "drivers." These drivers, i.e., the governing parameters, determine the value of the failure parameter. The drivers usually include geometry and dimensions, loads and environmental conditions, and relevant material properties for the operating environment.

In this probabilistic approach, the drivers are characterized by probability distributions. These probability distributions express uncertainty regarding driver values within the ranges of possible values. The accuracy of the failure model is treated as another driver which is probabilistically characterized. The probability distributions for the drivers are derived from available information regarding uncertainty of their values. The drivers are characterized using the information that exists at the time of the analysis. There is no specific information requirement for any driver.

The driver distributions reflect incomplete knowledge and limited information regarding driver values as well as intrinsic variability. The criteria of not overstating the available information in the driver probability distributions must be observed in order to appropriately represent the risk that results from incomplete knowledge and limited information.

Performance, weight, and cost requirements that propulsion systems must meet may not permit consistently, verifiably conservative values for analysis parameters to be used in all cases. Deterministic analyses for such applications must be "calibrated" by means of directly relevant past experience with applications that are similar in terms of the knowledge of input parameters, the validity of engineering models under the conditions of an application, and variability of manufacturing processes.

When deterministic analyses are used in applications that are removed from the directly relevant experience base, as is often the case for launch vehicle propulsion systems, the uncertainty or risk associated with their results increases. Since a deterministic analysis provides no quantitative risk estimate, an assessment of risk incurred as a result of having chosen any specific set of values for the governing parameters of the analysis must be left to the vicissitudes of judgment formed in the absence of directly relevant experience.

Deterministic analyses of failure modes under such conditions of limited information thus becomes arbitrary. Launch vehicle propulsion systems are invariably subject to some number of failure modes for which the governing parameters may not be well known, e.g.,

the knowledge of loads and/or local environments may be significantly uncertain and the validity of analytical models used to characterize failure phenomena may be questionable. Under such conditions of limited information and uncertain analyses, the implicit consideration of risk by means of qualitative judgments based on deterministic analysis of failure modes is inadequate.

In contrast, the PFA Methodology quantitatively accounts for driver specification error through appropriate formulation of the driver probability distribution. Application of a Monte Carlo technique using the driver distributions, coupled with the engineering model, produces a set of simulated failures. These simulated failures are then fit to a parametric failure distribution which is treated as a Bayesian prior distribution. This prior distribution is then modified using Bayesian updating to incorporate test and flight experience. The result is a posterior probability distribution for the failure mode. Overall mission risk can be estimated by aggregation of critical failure mode results.

The resultant risk may be judged to be acceptable or unacceptable. If risk is unacceptable, the framework of the PFA analysis facilitates the procedure for choosing actions which will reduce the risk. The effect on risk, for example, of acquiring additional data, improving the engineering model, or making design changes, can be determined directly and quantitatively.

Application of PFA Methodology to Debonding.

At this writing, a flowchart for the engineering model for debonding has been developed. The model, shown in Figure 2, incorporates the processes described in the debond failure mode description above. Standard nomenclature is used: K_I and K_{II} are the mode I and mode II stress intensity factors, respectively. It is expected that some parts of the flowchart will require more detail while other parts represent unnecessary detail, and will be revised. For example, finite element and finite difference calculations are incorporated in the flowchart loop. These would be extremely demanding of computational time if they were required to be within the Monte Carlo analysis. Considerations of this type have been encountered before (refs. 2 & 3), and some techniques have been found which help minimize cpu time. Modifications of the Monte Carlo approach and alternative methods will also be considered.

It is important to reiterate that the risk assessment will be made using available information--no additional program to develop data is required (although advantage will be taken of such opportunities, in particular appropriate information from the Solid Propellant Integrity Program, ref. 10, will be utilized). For example, variability or scarcity of data in material properties can be accounted for statistically. If the resultant risk is unacceptable, the structure of the PFA methodology can suggest options which will have the greatest impact on the risk estimate. Possible options include design or processing changes, improved inspection capability, acquisition of additional materials characterization data, and reduction in uncertainty of engineering models.

Interaction with experts in the SRM industry have been and will continue to play an important role in technical development of this program.

Acknowledgments

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DEBOND FAILURE PROCESSES

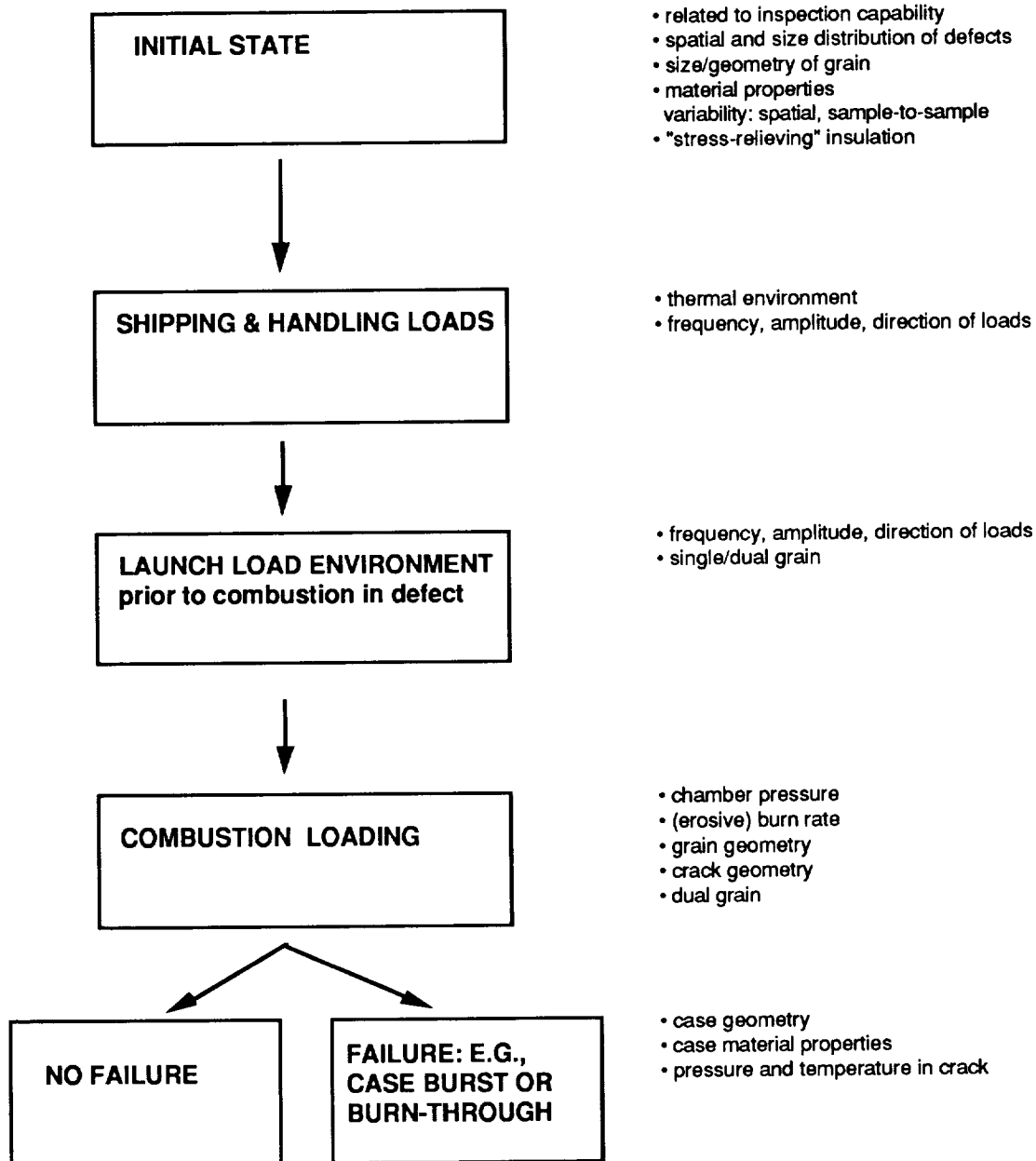


Figure 1. Diagram of debonding processes. Comments to the right of the boxes represent a partial list of relevant factors.

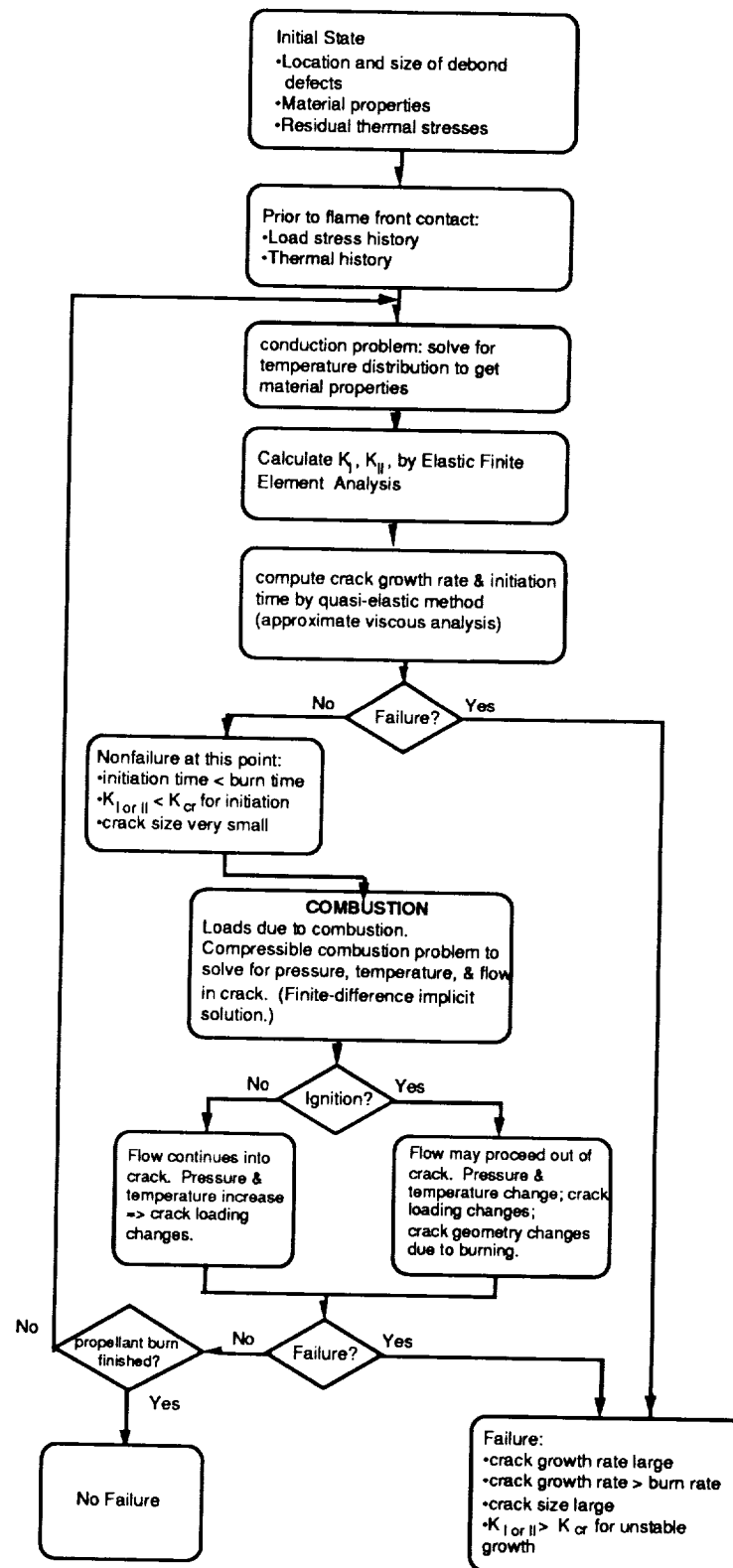


Figure 2. Flowchart of PFA debond model.

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